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NUCLEON DECAY IN GUT AND NON-GUT SUSY MODELS

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I first emphasize the importance of searching for nucleon decay in the context of supersymmetric models. The status of minimal SUSY SU(5) model is reviewed, which can be definitively ruled out by a combination of superKamiokande and LEP-2 experiments. Non-minimal models may provide some suppression in the nucleon decay rates, but there is still a good chance for superKamiokande. I point out that the operators suppressed even by the Planck-scale are too large. We need a suppression mechanism for the operators at the level of 10^{-7}, and the mechanism, I argue, may well be a flavor symmetry. A particular example predicts $p \to K^0 e^+$ to be the dominant mode which does not arise in GUT models.

1 Introduction

Now superKamiokande is up and running very well! This is the good news which we heard at this conference. And it is expected to extend the reach on nucleon decay by more than an order of magnitude. My talk is devoted to discuss the following questions about the nucleon decay in the context of suprsymmetric models. How important is it to look for nucleon decay? What decay modes are expected or interesting? What is the current status of various models which predict nucleon decay?

2 Why Nucleon Decay?

Here I would like to remind you why it is so important and exciting to look for nucleon decay experimentally.

There are at least three reasons why nucleons may decay. First, we have seen a dramatic success of supersymmetric grand unified theory (SUSY-GUT) in predicting $\sin^2\theta_W$. If we take this hint seriously, we expect to see nucleon decay since SUSY-GUTs predict nucleon decay at an observable rate. Second, the quantum gravity effects are believed to break any global symmetries, and hence the baryon and/or lepton numbers are also likely to be broken. Third, we know that our Universe is dominantly made up of baryons rather than anti-baryons with a possible exception inside the Tevatron ring. If we would like to understand this asymmetry as a result of dynamics in the Early Universe, there must be interactions which violate baryon number conservation which were effective at high temperatures.

I must admit none of the above arguments are without loopholes. First motivation based on the apparent gauge unification may not necessarily mean that there is a field theoretical grand unification. It may be explained by, for instance, string unification where you do not have a simple large gauge group into which the standard model gauge groups are embedded. The second argument may not necessarily imply the existence of nucleon decay process. The baryon number may be effectively preserved due to gauge symmetries, either continuous (such as gauged $U(1)_B$ symmetry[1]) or discrete,[2] which are stable against quantum gravitational effects. Finally, the last motivation may be void if the cosmic baryon asymmetry is generated due to the sphaleron effect from the primordial lepton asymmetry, which may be generated due to the decay of right-handed neutrinos[3] or Affleck–Dine mechanism.[4]

However, I should also emphasize the following simple fact which by itself makes the search for nucleon decay very interesting in the supersymmetric models. We are probing physics at extremely high energy scales by looking for nucleon decay. In particular, the current limit on nucleon decay has a sensitivity up to 10^{26} GeV! Of course it does not make much sense to talk about such a scale much beyond the Planck scale. I will explain below where this scale comes from. In any case, such an extreme sensitivity to high-energy physics is hard to beat by any other means, and this is what makes the nucleon decay such an interesting process to look for.

3 $D = 5$ or $D = 6$

Let me briefly discuss the "classic" prediction of a grand unified theory how a nucleon might decay. In SU(5) GUT, the standard model gauge groups are embedded into a simple SU(5) group which has additional gauge bosons beyond those in the standard model. The additional gauge bosons mediate a process such as $uu \to e^+\bar{d}$. This process can be effectively described by a $D = 6$ four-fermion operator

$$\mathcal{L} = \frac{1}{M^2} uude, \tag{1}$$

where M is a high mass scale such as the GUT-scale. By adding another down quark as a spectator to this process, one obtains a decay $p \to e^+\pi^0$. The current lower limit on proton partial lifetime implies the GUT-scale must be larger than 1.5×10^{15} GeV where I estimated the bound conservatively using formulae given in.[5] Because the operator has a suppression by two powers of a high mass scale, the proton decay rate is given roughly by $\Gamma_p \sim m_p^5/M^4$ and suppressed by the fourth power. It is not easy to extend the reach to higher mass scale in this case.

On the other hand, supersymmetric models tend to have operators which mediate nucleon decay with less suppression by a high mass scale, such as

$$\mathcal{L} = \frac{\lambda}{M} qq\tilde{q}\tilde{l} \tag{2}$$

with λ a coupling constant. This type of operators has $D = 5$ and they are called $D = 5$ operators. The squark/slepton created virtually by this type of operators must be converted to quark/lepton by an exchange of gauginos to let a nucleon decay. As a result, the nucleon decay rate is given roughly by $\Gamma_p \sim \lambda^2 m_p^5/M^2/m_{SUSY}^2$. Since it is suppressed only by two powers in a high mass scale, we can probe much higher M with these operators. In fact, if we take $\lambda \simeq 1$, and by doing an extremely conservative analysis as the one which I will describe shortly in the case of minimal SUSY SU(5) GUT, one obtains a lower bound on M:

$$M > 8 \times 10^{23} \text{ GeV}. \tag{3}$$

Possible existence of such a $D = 5$ operator was first pointed out in the context of SUSY-GUT.[6] When the standard model gauge groups are embedded into SU(5), the Higgs doublets H which break the electroweak symmetry are embedded into **5** and $\mathbf{5}^*$ representations of SU(5) which contain color-triplet Higgs bosons H_C. They further have their fermionic partners $\tilde{H}_C$ due to supersymmetry. The exchange of color-triplet Higgsinos generate operators suppressed only by one power in M_{GUT} because of the fermion propagator $\sim i/(\not{p} - M)$. Since the couplings of color-triplet Higgsinos to (s)quarks and (s)leptons are related to those of color-triplet Higgs bosons by supersymmetry and further to those of Higgs doublets by SU(5), we know the strengths of the couplings rather well. The most important $D = 5$ operator has a coefficient $\lambda_c \lambda_s \sin\theta_C / M_{H_C}$ where λ_c, λ_s are the Yukawa couplings of charm and strange quarks to the standard Higgs bosons and θ_C the Cabbibo angle. Therefore we can make precise predictions of nucleon decay rate in this situation for given values of M_{H_C}.

On the other hand, the quantum gravity effect may well generate effective non-renormalizable operators if they break global baryon and/or lepton number symmetry. They are likely to be suppressed by powers in the reduced Planck scale $M_* \equiv M_{Pl}/\sqrt{8\pi}$ because they are quantum gravity effects. They may arise also due to the exchange of heavy string states. Unless there is a reason for a suppression, we expect the coefficient of a $D = 5$ operator to be $1/M_*$ in this case.

I will discuss the consequence of $D = 5$ operators of GUT- and Planck-scale origin separately in the following sections.

Whatever the origin of a $D = 5$ operator is, there are a couple of characteristics common to nucleon decay via $D = 5$ operators. (1) It is sensitive to *extremely* high energy scales, as already mentioned above. Actually it is a phenomenological disaster if there is an operator with a coefficient of order $1/M_*$. Therefore, the current bound is already putting constraints on the physics at the Planck scale. (2) The final states of nucleon decays (almost) always involve kaons, either K^+ or K^0. This is due to the flavor SU(3) symmetry property

Table 1: Relative decay rates of nucleons in the Minimal SUSY SU(5)-GUT assuming there is no accidental cancellation in the amplitudes.

$p \to$	$K^+\bar{\nu}_\mu$	$\pi^+\bar{\nu}_\mu$	$K^0\mu^+$	K^0e^+
rel. rates	1	0.49	0.00069	$2.1 \cdot 10^{-6}$
$n \to$	$K^0\bar{\nu}_\mu$		$\pi^0\bar{\nu}_\mu$	
rel. rates	1.8		0.24	

of $D = 5$ operators. There is no $D = 5$ operator which consists of the first generation fields only; it identically vanishes. The quark which is not in the first generation but still light enough to be able to appear in the nucleon decay is the strange quark. (3) The rate depends on the superparticle spectrum, such as masses of squarks, sleptons and wino.

4 Minimal SUSY SU(5)

The nucleon decay rate can be worked out quantitatively[5] in the Minimal SUSY SU(5)-GUT.[7] As explained already, the $D = 5$ operators arise because of the exchange of the color-triplet Higgs(ino), and the dominant operator has the coefficient $\lambda_c \lambda_s \sin\theta_C / M_{H_C}$. There are four types of parameters which enter the calculation. (1) The Yukawa couplings λ_c and λ_s are known up to the dependence on $\tan\beta$. The amplitude is proportional to $1/\sin 2\beta$ which grows with $\tan\beta$. (2) The mass of the color-triplet Higgs M_{H_C} can be actually determined from the low-energy data only, namely the gauge coupling constants measured by LEP. At the one-loop level, it can be determined by the following formula[8]

$$(3\alpha_2^{-1} - 2\alpha_3^{-1} - \alpha_1^{-1})(m_Z) = \frac{1}{2\pi}\left(\frac{12}{5}\ln\frac{M_{H_C}}{m_Z} - 2\ln\frac{m_{SUSY}}{m_Z}\right). \quad (4)$$

The largest uncertainty is in $\alpha_3(m_Z)$, and therefore we put bounds as a function of $\alpha_3(m_Z)$. In practice, I use two-loop renormalization group equations. Note the positive correlation between $\alpha_3(m_Z)$ and M_{H_C}: the decay rate is larger for smaller $\alpha_3(m_Z)$. (3) We choose the most conservative choice of the superparticle mass spectrum which gives the smallest nucleon decay rate. The amplitude is proportional to $M_2/m_{\tilde{q}}^2$, and we take $M_2 \simeq 45$ GeV and $m_{\tilde{q}} \simeq 1$ TeV. (4) The matrix element β of the operator between a nucleon and a meson is not well known. The estimates vary as $\beta = 0.003$–0.03 GeV^3.[9] We again take the most conservative one $\beta = 0.003$ GeV^3. (5) We use the subdominant decay mode $n \to \pi^0\bar{\nu}_\mu$ instead of the dominant one $n \to K^0\bar{\nu}_\mu$ because there might be a partial cancellation in the amplitude between a diagram with charm (s)quark and one with top (s)quark.[10] For the case without such a cancellation, the relative decay ratios are given in the Table 1.

Based on very conservative assumptions as describe above, the allowed region[11] in $(\tan\beta, \alpha_3(m_Z))$ plane is given in Fig. 1. The experimental limit on nucleon decay puts a lower bound on M_{H_C} which is translated into the lower limit on $\alpha_3(m_Z)$ using the correlation. The bound is tighter for larger $\tan\beta$ because the amplitude grows. The two-sigma band of $\alpha_3(m_Z) = 0.118 \pm 0.003$ is shown. For a comparison, the preferred range from b-τ Yukawa unification is also shown for $m_t = 176$ GeV. They actually barely overlap for smaller m_t. The expected improvements by superKamiokande (dashed) and further by LEP-2 (dotted) are also shown. (An improved lower limit on M_2 from LEP-2 would make the amplitude larger $\sim M_2/m_{\tilde{q}}^2$.) The Minimal SUSY SU(5)-GUT can be definitively excluded by these experiments.

5 Non-minimal SUSY-GUT

There are many good reasons to discuss extensions of the minimal SUSY SU(5) GUT. Among them, there are two points directly relevant to the nucleon decay. (1) The triplet-doublet splitting problem. In minimal SUSY SU(5) GUT, one needs to fine-tune independent parameters at the level of 10^{-14} to keep Higgs doublets light while making the color-triplet Higgs heavy. (2) The wrong fermion mass relations. It predicts $m_s = m_\mu$ and $m_d = m_e$ at the GUT-scale, which are off from the phenomenologically preferred Georgi–Jarlskog relations $m_s = m_\mu/3$, $m_d = 3m_e$.

Solutions to the above-mentioned problems modify the predicted rate and branching ratios of the nucleon decay. One possible attempt to obtain Georgi–Jarlskog relations is to use the SU(5)-adjoint Higgs to construct an effective **45** Higgs

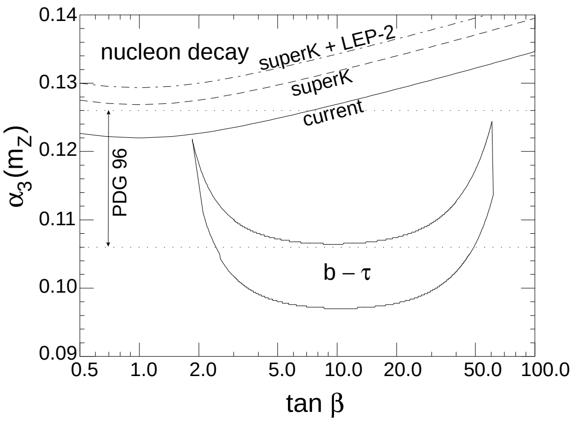

Figure 1: Excluded region on $(\tan\beta, \alpha_3(m_Z))$ space from nucleon decay based on very conservative assumptions as described in the text. Expected improvements from superKamiokande and LEP-2 are also shown. The range shown for $\alpha_3(m_Z)$ from PDG96 is two sigma range. The preferred region from $b-\tau$ unification is also shown for $m_t = 176$ GeV.

doublets as composites of ordinary Higgs doublets in **5** and the adjoint. This modification leads to a factor-of-two enhancement in the amplitude; a factor of four in the rate.[12] The relative branching ratios can be also different. It remains true that the $K^{+,0}\bar{\nu}_\mu$ modes are the dominant ones, while the $K^0\mu^+$ mode may be much less suppressed than in the minimal SU(5).[13,14]

There are various proposals to solve the triplet-doublet splitting problem, which lead to completely different nucleon decay phenomenology. I discuss three of them here. (1) The missing partner model,[15] (2) Dimopoulos–Wilczek–Srednicki mechanism,[16] and (3) flipped SU(5) model.[17]

In the missing partner model, one employs **75** representation to break SU(5) instead of the adjoint **24**, and further introduces **50** and **50*** representations which mix with the color-triplet Higgs to make them massive. Since the model involves such large representations, the size of the GUT-scale threshold corrections are significantly larger than that in the minimal model. And the correction changes the determination of the color-triplet Higgs mass as done in Eq. (4), and the measured values of the gauge coupling constants prefer larger M_{H_C} than in the minimal model.[18] In this case the proton decay rates are much more suppressed, by a few orders of magnitudes. One drawback of the model is that it becomes non-perturbative well below the Planck scale due to large representations and one needs to complicate the model further to keep it perturbative.[19] It is worth to recall that the minimal SU(5) model is marginally allowed only with very conservative assumptions made in the previous section. Even though there is an additional suppression to the proton decay rate in this class of models, the decay rate may still well be within the reach of superKamiokande experiment.

The mechanism proposed by Dimopoulos, Wilczek and further by Srednicki employs SO(10) unification with Higgs fields in adjoint and symmetric tensor representations which naturally keep Higgs doublets light. However, their model breaks SO(10) only to SU(3)×SU(2)$_L$×SU(2)$_R$×U(1)$_{B-L}$ and has to be extended to achieve the desired symmetry breaking down to the standard model gauge group. One of such extensions by Babu and Barr[20] eliminates $D=5$ operators entirely; but it involves rather complicated Higgs sector, and one needs to forbid some allowed interactions in the superpotential arbitrarily. A later attempt[21] to guarantee the special form of the superpotential by symmetries did not eliminate the $D=5$ operators entirely, but resulted in a weak suppression of the operators. Again in view of the very marginal situation in the minimal model, the decay rate could be within the reach of the superKamiokande.

The flipped SU(5) model solves the triplet-doublet splitting problem in a way that it also eliminates the $D=5$ operators entirely. A possible problem with this model is that the gauge unification becomes more or less an accident rather than a prediction. On the other hand, the elimination of the $D=5$ operator is a natural consequence of the structure of the Higgs sector, and is rather a robust prediction of the model except the Planck-scale effects which will be discussed below. An interesting feature of the model is that the GUT-scale is determined by α_2 and α_3 and hence can be *lower* than the scale in the minimal SU(5) which is determined by α_2 and α_1. Since the model does not predict the relation between α_1 and $\alpha_{SU(5)}$, α_1 does not need to meet with the other coupling constants at the same scale. Therefore, the GUT-scale can be as low as $M_{GUT}^{\rm flipped} = 4$–$20 \times 10^{15}$ GeV. If the M_{GUT} is at the low side within this range, the $D=6$ operator may be observable in the $\pi^0 e^+$ mode,[22] since the superKamiokande is expected to extend the reach by a factor of 20.

6 Planck-scale Operators

As I mentioned at the beginning of the talk, the Planck-scale effects may generate $D = 5$ operators suppressed by the reduced Planck scale $M_* = 2 \times 10^{18}$ GeV. Even when there is no color-triplet Higgs, such as in string compactifications which breaks the gauge group down to the standard model (with possible U(1) factors) directly, the higher string excitations may give rise to effective non-renormalizable $D = 5$ operators which break baryon- and/or lepton-number symmetries. For $D = 5$ operators which involve first- and second-generation fields, $1/M_*$ suppression is far from enough: one needs a coupling constant of order 10^{-7} to keep the nucleons stable enough as required by experiments.

It is a serious question in supersymmetry phenomenology why the Planck-scale $D = 5$ operators are so much suppressed. Even though there are ways to forbid them by employing discrete gauge symmetries,[2] I prefer a different type of solution: the $D = 5$ operators are suppressed because of the same reason why the Yukawa couplings of light generations are suppressed.[23] One way to understand why the Yukawa couplings are so small, such as 10^{-6} for the case of the electron, may be a natural consequence of an approximate flavor symmetry. If a flavor symmetry exists and is only weakly broken to explain smallness of the Yukawa couplings, the same flavor symmetry can well suppress the $D = 5$ operators at the Planck-scale. We[23] speculated that the $D = 5$ operators with such a flavor origin may have very different flavor structure from those in the GUT models, and may lead to quite different decay modes like $p \to K^0 e^+$.

Hall and myself constructed a model with $(S_3)^3$ symmetry[24] in which the hierarchical Yukawa matrices can be understood as a consequence of sequential breaking of the flavor symmetry while the symmetry preserves sufficient degeneracy among the squarks and sleptons to suppress flavor-changing neutral currents. It happened that the flavor symmetry in this model also suppresses $D = 5$ operators to the level of about 1/9 of the minimal SU(5)model, so that it can well be within the reach of superKamiokande.[25] What is particularly interesting in this model is that it predicts $p \to K^0 e^+$ as the *dominant* mode over the $K^+ \bar{\nu}$, while $n \to K^0 \bar{\nu}_e$ is the dominant mode in neutron decay with a comparable rate.

Finally, I would like to make a brief comment on the R-parity. The R-parity is usually imposed on supersymmetric models as means to forbid dangerous $D = 4$ (!) operators which break baryon- or lepton-numbers. Indeed, such operators must be highly suppressed $< 10^{-13}$ if both B- and L-violating operators are present. However, a flavor symmetry may suppress these operators drastically as well,[23] and explicit examples were constructed.[26]

7 Conclusion

I reminded you the importance of search for nucleon decay in the context of supersymmetric theories. Contrary to the non-supersymmetric models, nucleon decay probes physics even at the Planck-scale because of possible $D = 5$ operators. In fact, the current limit requires the scale of baryon number violation to be larger than 10^{24} GeV or more if the operators are unsuppressed. We expect $K\bar{\nu}$ modes to be dominant in many supersymmetric models.

The minimal SUSY SU(5)-GUT is nearly excluded by a combination of $\alpha_3(m_Z)$ prediction and the nucleon decay, and will be definitively with superKamiokande and LEP-2. Non-minimal GUT models may suppress the nucleon decay rates, but still the rates could be within the reach of superKamiokande. A dark horse example is the flipped SU(5) model which may give $\pi^0 e^+$ mode at an observable rate.

Since the Planck-scale operators give nucleon decay rates which are too large, one needs a suppression mechanism. I argued that a flavor symmetry is a likely mechanism to provide an adequate suppression of the $D = 5$ operators, and they may give rise to exotic decay modes like $K^0 e^+$ which do not arise in GUT models.

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